NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Grid Forming Technology

Bulk Power System Reliability Considerations

December 2021

RELIABILITY | RESILIENCE | SECURITY




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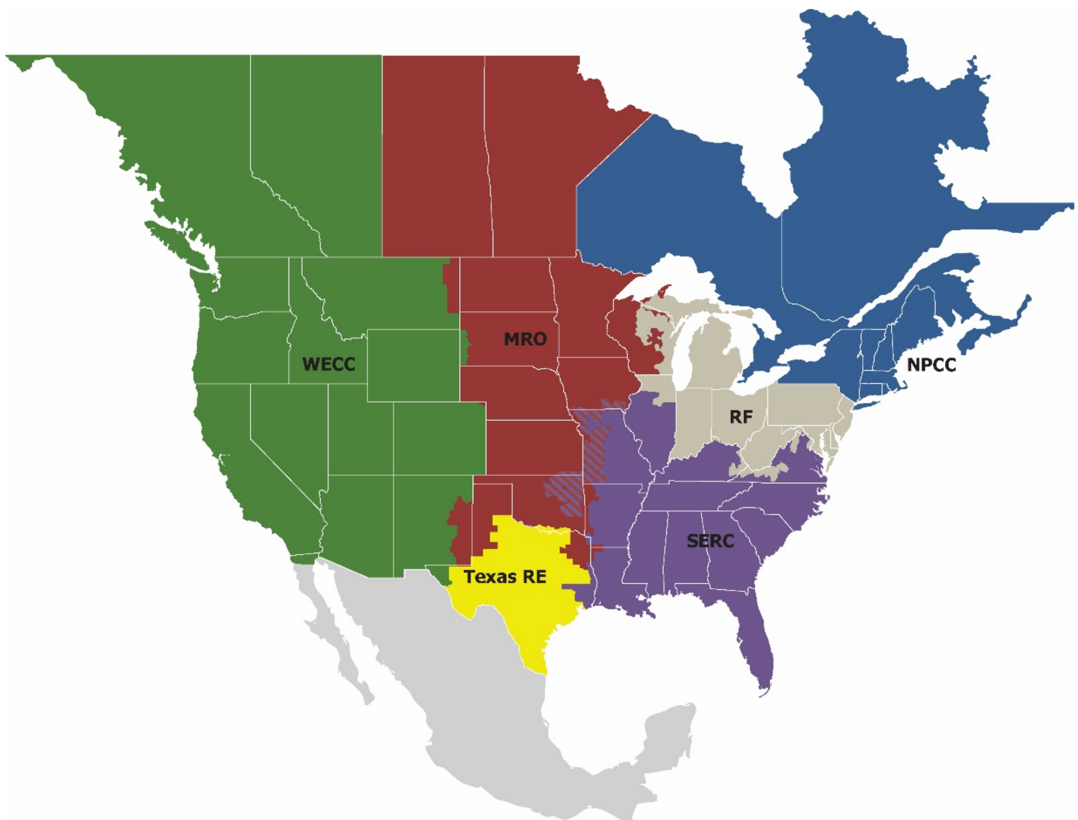
Preface

Electricity is a key component of the fabric of modern society and the Electric Reliability Organization (ERO) Enterprise serves to strengthen that fabric. The vision for the ERO Enterprise, which is comprised of the North American Electric Reliability Corporation (NERC) and the six Regional Entities (REs), is a highly reliable and secure North American bulk power system (BPS). Our mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid.

Reliability | Resilience | Security
Because nearly 400 million citizens in North America are counting on us

The North American BPS is made up of six RE boundaries as shown on the map and corresponding table below. The multicolored area denotes overlap as some load-serving entities participate in one Region while associated Transmission Owners (TO)/Operators (TOP) participate in another.



MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
Texas RE	Texas Reliability Entity
WECC	Western Electricity Coordinating Council

Executive Summary

As inverter-based resource (IBR) penetrations continue to grow across North America, grid dynamics and control strategies have also adapted and advanced over the recent years. One such technology that is now gaining momentum is grid-forming (GFM) inverter technology. GFM inverters have been widely researched in battery energy storage systems (BESS), wind power plants, solar photovoltaic (PV) plants, and hybrid[1] plants. Furthermore, there are several installed projects where GFM functions have been successfully tested, including extremely fast power injection in the inertial time frame in response to frequency events, islanded operation capability without synchronous generation, blackstart capability, and operation in parallel with grid-following (GFL) resources and synchronous machines. Widespread understanding of GFM controls and their impact on BPS performance is still in the early stages; however, the technology shows significant promise. Study findings from system conditions with high IBR penetrations show the benefits for GFM controls, and equipment vendors have commercially available products that can provide GFM capability. While GFM inverters still need to be studied and tuned to specific system conditions (similarly to GFL controls), they do have advantages compared to the GFL control schemes applied in nearly all existing IBRs today. GFM IBRs are expected to be beneficial for increasing IBR penetration levels and will likely play an important role in contributing to the stability and reliability of the BPS under future high IBR penetration conditions.

There are presently no universally agreed upon definitions of GFL and GFM inverter controls in the industry. This white paper recommends the following definition:

> ***Grid Forming Control for BPS-Connected Inverter-Based Resources*** *are controls with the primary objective of maintaining an internal voltage phasor that is constant or nearly constant in the sub-transient to transient time frame. This allows the IBR to immediately respond to changes in the external system and maintain IBR control stability during challenging network conditions. The voltage phasor must be controlled to maintain synchronism with other devices in the grid and must also regulate active and reactive power appropriately to support the grid.*

GFM control are recommended to provide robust dynamic support[2] to the grid including (but not limited to) the following:

- Operation in low system strength condition
- Grid frequency and voltage stabilization
- Small signal stability damping to maintain power system stability
- Re-synchronization capability to restore and reconnect to the grid
- Fault ride through for large grid disturbance events with adequate fault current contribution as required by protection systems (if hardware limits allow)
- System restoration and blackstart capability (for some GFM inverters)

This white paper compares GFM and GFL IBR capability and their major performance characteristics and advantages. Currently, the most commonly used GFM control strategies of droop-based GFM control, virtual synchronous machine control, and virtual oscillator control are briefly summarized.[3] This white paper also provides recommendations for entities across North America to consider studying and deploying GFM technology to support BPS reliability and resilience with increasing IBR penetration levels.

[1] Hybrid plants are defined here as “a generating resource that is comprised of multiple generation or energy storage technologies controlled as a single entity and operated as a single resource behind a single POI.”: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline_BESS_Hybrid_Performance_Modeling_Studies_.pdf

[2] Some but not all of these capabilities can also be made available from GFL controls.

[3] For further details regarding actual installed GFM or GFL controls, readers should consult with original equipment manufacturers.

Key Takeaways and Recommendations

Table 1.1 lists a number of recommendations for industry action and the associated entities to which the recommendations are directed. These recommendations apply generally to entities involved with BPS-connected IBRs.

Table E.1: Recommendations and Applicability

Recommendation	Applicability
Installation of GFM Controls Functionality: Equipment manufacturers, particularly for BESS, should ensure that products being installed today are suited to support the rapidly evolving BPS in the future. Developers should consider installing GFM-capable equipment with the capability to enable this functionality in resources in the future if needed. Resources installed with GFL functionality enabled may need to be converted to GFM functionality in the future, particularly under high penetration of IBR conditions. Having this functionality available when needed will result in significantly lower operating costs for these types of operating conditions.	Equipment manufacturers, project developers, Generator Owners (GOs), Generator Operators (GOPs)
Use of GFM Technology in Low System Strength Conditions: Many areas of the grid are undergoing significant drops system strength (sometimes roughly quantified by short-circuit ratio (SCR))[4] with the retirement of synchronous generation. Deploying GFM controls on IBRs connecting in areas with low system strength is an effective solution to ensure voltage stability. Although GFL controls can be tuned to reliably operate in areas with a low short-circuit ratio to meet interconnection requirements, GFL controls fundamentally require some minimum system strength to maintain stable operation. GFM inverters also require tuning but may unlock higher levels of IBR penetration in the future at lower overall cost.	Equipment manufacturers, project developers, GOs, TOs, Transmission Planners (TP), Planning Committees (PC), TOPs, Reliability Coordinators (RC)
Accurate Modeling of GFM Controls: Reliable interconnection of GFM-capable IBRs is incumbent on the ability to study their interaction with and support to the BPS prior to the resources being interconnected. It is critical that accurate models are developed and provided to the TPs and PCs for studying these resources during the interconnection process. Accurate Positive sequence dynamic models and electromagnetic transient (EMT) models should be developed, validated, and benchmarked against each other by the GOs, TPs, and PCs. This includes sufficient documentation regarding the control strategy and the performance of the resource during large signal disturbances. TPs and PCs should improve their modeling requirements and model quality checks to ensure these are also applicable to GFM technology. All IBRs, particularly those with the capability to operate with GFM controls, should provide accurate, validated, and high-quality positive sequence and EMT models for future reliability study needs.	Equipment manufacturers, developers, GOs, TPs, PCs
Improved Interconnection Process and Study Practices for GFM IBRs: All TOs, in coordination with their TPs and PCs, should develop a process for determining situations and locations where GFM technology is needed (or beneficial) and appropriate study approaches for qualifying and quantifying the potential benefits of GFM technology. This process should be implemented as part of the interconnection requirements and study process per NERC FAC-001 and FAC-002 Reliability Standards. Use of GFM controls should be considered as one of many	TOs, TPs, PCs

[4] https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/Short_Circuit_whitepaper_Final_1_26_18.pdf

Table E.1: Recommendations and Applicability	
Recommendation	**Applicability**
solution options to mitigate potential reliability issues. In some areas, particularly under high IBR penetration conditions, use of GFM may be a cost-effective and necessary solution for controls stability issues as well as other grid reliability and resilience issues. TPs and PCs will need to perform detailed studies of future operating conditions to determine the need and benefits for GFM IBRs among other solution options. This will require both detailed positive sequence and detailed EMT studies with sufficient model validation and model quality checks. These activities will require additional time, new tools, and expertise and likely will need improvements to the interconnection process to enable these activities.	
Inverter-Based Resource Performance Working Group Focus on GFM Interconnection Requirements and Standardized Processes: The Inverter-Based Resource Performance Working Group should develop a set of standardized processes, recommended practices related to establishing requirements, and studies with GFM IBRs during the interconnection process. This guidance material should support equipment manufacturers, GOs, developers, TPs, and PCs in their activities to interconnect resources leveraging GFM technology.	NERC Inverter-Based Resource Performance Working Group
Unlocking GFM Capability by Improved Incentive Structures: A significant challenge with leveraging GFM capability is the ability to implement the technology at additional cost while appropriately allocating the cost in situations where benefits are socialized to many different entities. For example, the installation of GFM controls at one facility (or multiple facilities) could help mitigate the need for curtailment or transmission system upgrades across a larger geographical area that could be studied and quantified. We recommend that FERC and wholesale electricity markets (i.e., ISO/RTOs) should evaluate opportunities for including GFM controls as a "grid enhancing technology" to support BPS reliability where the benefits of implementing the GFM technology impact many other entities. This will help break down barriers that currently may be hindering the implementation of this technology on a larger scale.	FERC, ISO/RTOs
Future Research, Work Needed: GFM control is an evolving technology and will continue to require additional research moving forward. This includes, but is not limited to, the following: • Appropriate GFM IBR designs • GFM control tuning • Control interactions of multiple GFM IBRs and overall system stability • Coordination of GFM and GFL IBRs along with synchronous generators still in operation • Levels of current, power, and energy headroom needed to extract the maximum benefit of GFM controls • Levels of GFM IBR capacity needed to obtain the desired benefits for a given grid condition	Research institutions, national laboratories, U.S. Department of Energy, academic institutes, etc.

Table E.1: Recommendations and Applicability	
Recommendation	**Applicability**
• The role of GFM IBR versus synchronous condensers to strengthen the grid • Review and revision of interconnection standards to accommodate GFM IBRs • Metrics for quantifying system strength that account for GFM benefits as well as a metric for quantifying the stabilizing benefit of GFM IBRs, GFL IBRs, and synchronous machines • Methods for planning and maintaining the stability of high IBR penetration systems • Impact of GFM controls on protection system operations in high-IBR grids as well as recommended magnitudes, durations, and electrical characteristics of GFM IBR fault responses • Control strategies for blackstart using GFM IBRs (where needed)	

Background

Today's bulk electric grid is quickly changing with the retirement of synchronous generators (SG) and the rapidly increasing deployment of IBRs, such as wind plants, solar PV, BESS, and hybrid plants. In today's power system, SGs along with their auxiliary control loops/elements provide many grid services, such as inertial response (i.e., use of rotational kinetic energy) to slow down initial rate of change of frequency (ROCOF) after large generation trip events, primary frequency response (PFR) to stabilize grid frequency, grid voltage support, power oscillation damping, and sourcing of negative sequence current. Furthermore, traditional protection relay algorithms have been designed and tuned based on the high and predictably consistent short-circuit contribution of synchronous generators and other rotating machines to grid short-circuit disturbances. With increasing GFL IBR deployment, the reduced number of strong voltage sources, reduced inertial energy storage, and decreased short-circuit current will impact grid stability for large and small system disturbances and system protection.

GFL inverter controls are used in most grid-connected IBRs today. GFL typically includes a fast current control loop and a phase-locked loop (PLL). The control objective of the current loop is to achieve fast regulation of the IBR output current, and the control objective of the PLL is to synchronize the IBR output current with the grid voltage and to provide the phase information for the internal current control loops. GFL IBR converters are typically represented as controlled current sources. Due to this control structure, there is a delay of the PLL phase information and voltage information calculation. Therefore, GFL controls cannot instantaneously change IBR's active and reactive current output. Due to this fundamental limitation, GFL IBR performance is related to and dependent on the grid strength, control topology, and tuning of control parameters.

It has been shown that GFL controls become unstable under certain low system-strength[5, 6] conditions. The PLL-based high voltage direct current converters' performance has also been studied in low-strength scenarios based on the simplified Great Britain transmission network and the CIGRE-developed voltage source converter model by National Grid Electricity System Operator.[7] This study shows that there is an increasing stability risk for GFL IBRs as the system strength is decreasing.

To address GFL IBR stability issues, the robustness of IBR controls have been continuously improved by original equipment manufacturers (OEM) by tuning the IBR controller parameters and switching to more robust controllers and PLL architectures. These changes can help improve project stability in low system-strength conditions for normal or after credible contingencies at moderate IBR penetration levels. However, at higher penetration levels, GFL-controlled IBRs could become inadequate for maintaining grid stability.

The dynamic behavior of IBRs in the transient time frame is governed by the speed and accuracy of its signal measurements and communication quantities, robustness of internal signal processing algorithms, control topology, and the parameters of the controllers. Every IBR control system topology and parameter value set has a finite region of stability in terms of system strength and system inertial strength. As penetrations of GFL IBRs continue to grow, GFL IBRs will be challenged to maintain system stability without other supporting equipment. However, particularly in areas of decreasing short-circuit strength, GFM IBRs may be able to expand the region of stability or help support the grid in these areas.

Compared to GFL, GFM most commonly uses an instantaneously measured voltage signal rather than a processed signal from a PLL in a GFL inverter. GFM response and support to the grid are instantaneous in the transient time

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[5] System strength typically refers either to a high source impedance between the GFL IBR and the main grid voltage source.

[6] "Appendix D – Hornsea Technical Report Submitted by Orsted (into the performance of windfarm)": https://www.nationalgrideso.com/document/152351/download

[7] https://www.nationalgrideso.com/document/102876/download

frame. GFM technology[8,9,10] has been recently proposed in the IBR industry for use in parallel with the BPS[11] that, when mature, is expected to address the majority of the risks and concerns of high (up to 100%) IBR penetration grid operation and stability with coordinated control and appropriate studies. As many as seven different GFM architectures have been described[12] and field experience with GFM IBRs is being accumulated.[13,14] Because of the expected benefits of GFM IBR controls, interest in them is high and increasing.

For example, the U.S. Department of Energy announced funding for a consortium to advance the research, development, and commercialization of IBR grid-forming technologies to enhance power systems operation in August 2021.[15] National Renewable Energy Laboratory's *Research Roadmap on Grid-Forming Inverters* report[16] provides a roadmap on GFM controls, IBR's impact on grid stability, and the evaluation of crucial system interactions for the future grid that will be comprised of the combination of synchronous generators and GFM as well as GFL inverter-based resources.

Great Britain is developing the grid code modification GC0137 to add requirements for GFM IBRs and high voltage direct current systems[17] to ensure stable and reliable operation of the grid with high penetration of IBRs (combination of GFL, GFM, and SGs).[18,19] The GFM specifications are being developed as non-mandatory, and GFM capability is expected to be procured as a market product or as requests for proposals[20] in some cases. The GFM basic concept, functions, project experiences, differences from GFL, and specification requirements for grid code considerations were presented in the ESIG Spring Workshop 2021.[21]

Australia has also been actively developing strategies to use GFM IBRs to support high IBR penetration into the power system. Recent research has shown that GFM IBRs provide a successful alternative to synchronous condensers that have traditionally been used to provide system strength and voltage support.[22] Australia continues to explore numerous options for increasing system strength.[23]

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[8] J. Matevosyan, et al., "Grid-Forming Inverters: Are They the Key for High Renewable Penetration?" in IEEE Power and Energy Magazine, vol. 17, no. 6, pp. 89–98, November–December 2019. https://ieeexplore.ieee.org/document/8879610
[9] https://www.nrel.gov/docs/fy21osti/73476.pdf
[10] David Roop, "Weak Grids and Grid Forming Converters", Feb, 2021. https://cdn.misoenergy.org/20210216%20New%20Approaches%20Workshop%20Item%2005c%20VSCs%20and%20Weak%20Grid%20and%20Grid%20Forming%20Solutions523105.pdf
[11] GFM inverter operation in off-grid and islanded applications has been widespread for decades.
[12] Peter Unruh etc., "Overview on Grid Forming Inverter Control Methods", May 2020. https://doi.org/10.3390/en13102589
[13] A. Roscoe, et al., "Practical Experience of Operating a Grid Forming Wind Park and its Response to System Events" in Proc. 18th Wind Intgr. Workshop, Dublin, Ireland, Oct. 2019.
[14] A. Roscoe, et al., "Practical Experience of Operating a Grid Forming Wind Park and its Response to System Events" in Proc. 18th Wind Intgr. Workshop, Dublin, Ireland, Oct. 2019.
[15] https://www.energy.gov/eere/solar/funding-opportunity-announcement-solar-energy-technologies-office-fiscal-year-2021
[16] https://www.nrel.gov/docs/fy21osti/73476.pdf
[17] GB GC0137: Draft Final Modification Report and Annexes, Oct. 2021. GC0137: Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability (formerly Virtual Synchronous Machine/VSM Capability) | National Grid ESO
[18] R. Ierna, et al., "Effects of VSM Convertor Control on Penetration Limits of Non-Synchronous Generation in the GB Power System", 15th Wind Integration Workshop, 2016.
[19] https://www.h2020-migrate.eu/downloads.html (D3.2, D3.3, D3.6)
[20] https://www.hawaiianelectric.com/clean-energy-hawaii/selling-power-to-the-utility/competitive-bidding-for-system-resources/competitive-bidding-archived-rfp-information/stage-2-rfps
[21] https://www.esig.energy/event/2021-spring-technical-workshop/
[22] https://aemo.com.au/-/media/files/initiatives/engineering-framework/2021/application-of-advanced-grid-scale-inverters-in-the-nem.pdf
[23] https://arena.gov.au/renewable-energy/system-security-reliability/

IBR OEMs and North American research organizations are also developing GFM positive sequence models for GFM IBRs interconnection studies and large grid stability studies,[24,25] and the National Grid Electricity System Operator applied the simplified GFM positive sequence model in the Great Britain grid for the high penetration of IBR scenarios in their planning studies.[26] While positive sequence models can capture many aspects of GFM behavior, positive sequence models are fundamentally limited in their ability and accuracy compared to EMT model. In many situations, GFM EMT models are needed.

There are many different ways to develop and bring grid friendly IBR controls to real projects and academic research. This white paper defines "grid forming controls" and provides an overview of GFM IBR performance features expected from the BPS point of view. The GFM IBR functions, capabilities, impacts, and application benefits to the future high IBR penetration grid are summarized.

[24] https://www.wecc.org/Administrative/Du-%20Droop%20Controlled%20Grid%20Forming%20Inverters.pdf

[25] D. Ramasubramanian, P. Pourbeik, E. Farantatos and A. Gaikwad, "Simulation of 100% Inverter-Based Resource Grids With Positive Sequence Modeling," in IEEE Electrification Magazine, vol. 9, no. 2, pp. 62-71, June 2021.doi: 10.1109/MELE.2021.3070938

[26] https://www.nationalgrid.com/sites/default/files/documents/GC0100%20Annex%209%20%20VSM_0.pdf

Chapter 1: Definition and Characteristics of GFM

GFM Definition

GFM control for BPS-connected IBRs is defined in this document as follows:

- The primary objective of GFM control for BPS-connected IBRs is to maintain an internal voltage phasor that is constant or nearly constant in the sub-transient to transient time frame. This allows the IBR to immediately respond to changes in the external system and maintain IBR control stability during challenging network conditions. The voltage phasor must be controlled to maintain synchronism with other devices in the grid and must also regulate active and reactive power appropriately to support the grid.

GFM IBRs could be expected to have many of the following functions and characteristics:[27, 28, 29, 30]

- GFM IBRs create open circuit voltage sources. A GFM IBR facility can be capable of operating in islanded mode so that the IBR can serve its own auxiliary load and the connected loads in the absence of a synchronous resource or other GFM IBR support for the isolated grid conditions. With this characteristic, IBR can operate in a stable manner without the need for synchronous machines.[31]
- A GFM IBR can be controlled to synchronize and stably operate with other resources in the grid and different types of loads. These other resources include conventional synchronous machines and other GFM or GFL IBRs.
- Upon the occurrence of a large load step or generation trip event, a GFM IBR could contribute towards arresting the decline, increasing the frequency, and recovering frequency to the nominal value, assuming that energy and power margins are available.
- A GFM IBR would contribute towards provision of reactive power support and voltage regulation within the continuous operation region and outside the continuous operating region to some degree, thus aiding fast and stable voltage recovery after a fault.
- GFM IBRs also reduce adverse converter control interactions among GFM IBRs, GFL IBRs, other power electronic devices, and rotating machines on the grid.
- GFM IBRs provide the prescribed level of oscillation damping within the grid. As the IBR characteristics and penetration level change the grid, interactions or oscillation modes could change. Frequent studies and analysis may be required to verify the damping levels and adjust controls accordingly.
- GRM IBRs provide active low-order harmonics cancellation.
- GFM IBRs provide blackstart capability if needed and designed for this purpose[32,33]

[27] Some but not all of these capabilities can also be made available from GFL IBRs.
[28] Synchronous Energy Storage System with Inertia Capabilities for Angle, Voltage and Frequency Stabilization in Power Grids", 11th Solar & Storage Integration Workshop, 28. September 2021, Berlin, Germany
[29] PVPS PV as an ancillary service provider: https://iea-pvps.org/key-topics/pv-as-an-ancillary-service-provider/
[30] Grid Forming Inverters: EPRI Tutorial, EPRI, Palo Alto, CA: 2020, 3002018676: https://www.epri.com/research/products/000000003002018676.
[31] A. Hoke et al., "Inverter-Based Operation of Maui: Electromagnetic Transient Simulations": https://www.nrel.gov/docs/fy21osti/79852.pdf
[32] Additional considerations (e.g., energy assurance, dedicated blackstart control functionality, inverter overcurrent capability) would need to be taken into account for blackstart resources; however, the ability for GFM to operate in a standalone manner and reliably transition to grid-connected operation is a critical factor in its use during system restoration.
[33] "Blackstart and System Restoration using Inverter Based Resources: Supply of critical load", NERC IRPWG, July 2021: https://www.nerc.com/comm/RSTC/IRPWG/IRPWG_Meeting_Presentations_-_2021_07_21.docx.pdf

High-Level Explanation of GFM and Comparison with GFL Controls

There are multiple types of GFM control strategies[34] as illustrated in Figure 1.1. These include, but are not limited to, the following:

- **Droop-Based GFM Control:**[35,36,37] GFM droop control is realized by active and reactive power droop control, which control the IBR voltage phasor frequency in proportion to the active power extracted from it. GFM reactive power droop control has similar logic for the Q-V relationship.
- **Virtual Synchronous Machine (VSM):**[38,39] VSM programs the IBR's control to emulate an SG's response so that the IBR can act similarly to an SG to provide an active power response that mimics a SG's expected contribution to a sudden generation loss, load change, or system fault.
- **Virtual Oscillator Control (VOC):**[40,41] VOC controls are inspired by the phenomenon of self-synchronization in networks of non-linear oscillators. VOC controls cause the IBR to act as a non-linear oscillator with a dead zone.

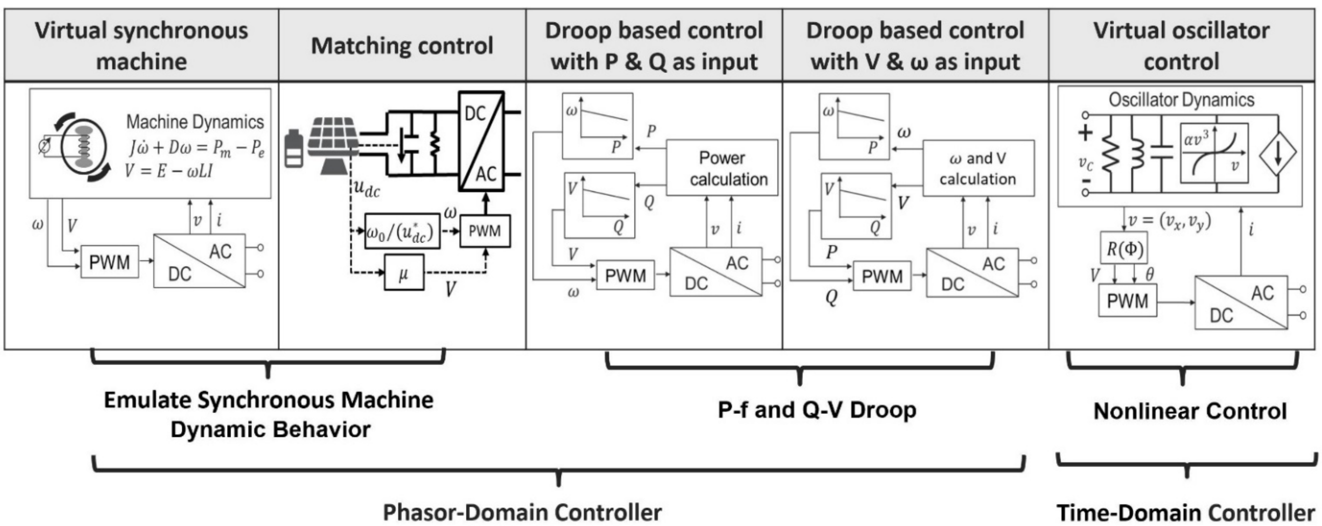

Figure 1.1: Different Types of GFM Control [Source: EPRI]

Figure 1.2 and Figure 1.3 are high-level examples of block diagrams for GFM and GFL control, respectively, and illustrate some of the similarities and differences between the different types of controls. Some of the main differentiations between GFM and GFL control are summarized in Table 1.1.

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[34] C. Cardozo, "From Grid-Forming Definition to Experimental Validation with a VSC", in Proc. 18th Wind Intgr. Workshop, Dublin, Ireland, Oct. 2019.

[35] Experiences with large grid forming inverters on various island and micro grid projects: https://hybridpowersystems.org/wp-content/uploads/sites/13/2019/06/3A_3_HYB19_017_presentation_Schoemann_Oliver_web.pdf

[36] D. Ramasubramanian, "Would Traditional Primary Frequency Response and Automatic Voltage Control Naturally help Usher in Grid Forming Control?," CIGRÉ Science & Engineering, vol. 20, pp. 52-60, February 2021

[37] Grid-Forming Inverters: A Critical Asset for the Power Grid, IEEE Journal of Emerging and Selected Topics in Power Electronics, June 2020.

[38] Zhong, Qing-Chang. "Virtual Synchronous Machines: A unified interface for grid integration." *IEEE Power Electronics Magazine* 3.4 (2016): 18-27: https://ieeexplore.ieee.org/abstract/document/7790991/

[39] https://standards.ieee.org/project/2988.html

[40] MIGRATE D3.3 - New options for existing system services and needs for new system services: https://www.h2020 migrate.eu/downloads.html

[41] Johnson, B. et al., "Comparison of virtual oscillator and droop control", In Proc. IEEE 18th Workshop on Control and Modeling for Power Electronics. NJ, USA, 2017.

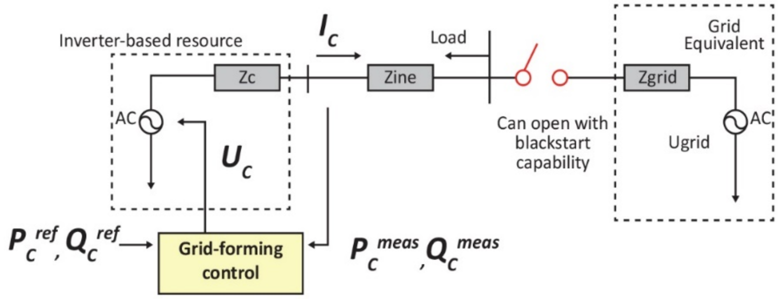

Figure 1.2: One method of GFM control

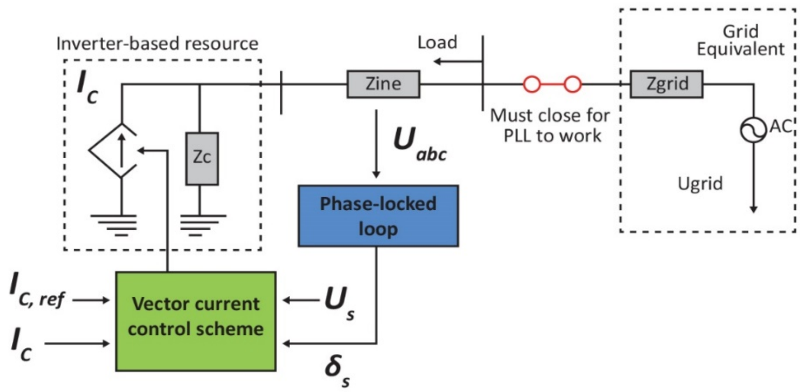

Figure 1.3: One method of GFL control

Table 1.1: GFM & GFL major difference comparison	
GFM	**GFL**
Control IBR terminal voltage magnitude and angle or frequency	Control IBR current magnitude and phase angle
May not use a PLL for synchronization	Needs PLL or equivalent
May be designed to operate standalone	Dependent on grid other resources to operate stably and provide grid support
Can operate grid at 100% IBR, provided some IBRs are GFM	Cannot operate grid at 100% GFL IBR penetration
Inherently provides fast energy injection in the inertial timeframe	Can provide fast frequency response (FFR) with a short time delay needed for frequency measurement and control response
Stable operation under very low grid strength conditions e.g., SCR<1 (still subject to power transmission constraints)	Stable operation region terminates at some minimum system strength e.g., SCR>1
Can serve as an initial blackstart resource if designed for that purpose	Cannot serve as an initial blackstart resource

Grid Forming Projects around the World

GFM control strategies and products are still being actively developed and commercialized by research organizations and OEMs. Although GFM IBRs have no unified control methods in the industry at present, there have been several GFM IBR projects installed in the field (or tested in simulations), and more IBR projects are being developed with GFM technology. Examples of existing projects deployed using GFM technology are briefly mentioned as follows:

- The VSM controlled Dalrymple Substation Battery[42] GFM project in South Australia started commercial operation in December 2018 and demonstrated that GFM IBR is not only capable of operating in low system-strength conditions (SCR<1) but also can improve grid reliability and provide security service with short-circuit current contribution, virtual inertia response, blackstart, and islanding operation capability.[43]
- The newly expanded Hornsdale Power Reserve has reported a successful BESS ROCOF function test (new "virtual machine mode") when it reacted to the grid disturbances created by the Callide coal plant explosion in Queensland in May 2021.[44]
- The California Imperial Irrigation District BESS (30 MW-20 MWh lithium-ion battery) project demonstrated blackstart capability in 2016. It is the first demonstration of a BESS black-starting a synchronous generator (44 MW combined-cycle natural gas turbine) to achieve synchronization in a U.S. utility.[45]
- GFM BESS frequency droop control and blackstart function have also been applied on a Caribbean Island with other renewable energy resources (PV and wind) as a hybrid IBR resource to reduce the use of diesel generation.[46]
- In Great Britain, controls for an existing 69 MW wind farm that consist of Type 4 full converter wind turbines were modified to GFM VSM.[47] The wind farm was successfully tested for virtual inertia capability providing ROCOF support, blackstart, and islanded operation capability.
- Droop-based GFM solar PV models have been applied to investigate GFM frequency support for the Hawaiian islands of Oahu[48] and Maui.[49]
- Hawaiian Electric Company plans to implement wide-spread GFM BESS technology throughout their island power systems by 2023. Significant work in specification, procurement, and detailed EMT studies have been completed. These detailed studies indicate that the GFM technology will be critical to allow the envisioned high renewable penetration scenarios to operate reliably.[50] Further work remains to examine additional operating scenarios and control tuning advances prior to commissioning in 2023.
- A 100% inverter-based microgrid[51] was constructed by American Electric Power in 2006. The GFM IBR separation from the grid and load step changes during islanded operation have been field tested and have shown good dynamic performance.[52] The derived GFM positive sequence models are used to assess the high penetration GFM IBR (65% of peak load) impact to microgrid transient, frequency, and voltage stability with a synchronous generator loss disturbance.

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[42] A 30 MW Grid Forming BESS Boosting Reliability in South Australia and Providing Market Services on the National Electricity Market", 18th Int'l Wind Integration Workshop, October 2019.

[43] https://www.escri-sa.com.au/globalassets/reports/grid-forming-energy-storage-webinar-escri-sa---july-2020.pdf

[44] https://reneweconomy-com-au.cdn.ampproject.org/c/s/reneweconomy.com.au/virtual-machine-hornsdale-battery-steps-in-to-protect-grid-after-callide-explosion/amp/

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Chapter 2: GFM IBR Challenges and Recommendations

GFM technology is rapidly evolving as new commercial products are being introduced, new research is furthering the understanding of different control topologies, and field tests are proving operational benefits. The industry is faced with opportunities to leverage GFM technology to ensure grid reliability and resilience with the increasing penetration of inverter-based resources. However, there are also challenges associated with effectively adopting any new technology. NERC provides the following recommendations for all entities across North America that are considering deploying GFM technology on their systems.

Capabilities and Performance

The following recommendations relate to the capabilities and performance associated with GFM technology:

- **GFM Technology Availability:** Although GFM technology has been used in remote and island electric grids for decades, this technology is still in the early stages of technology maturity and adoption in the BPS. OEMs are exploring different GFM controls and testing GFM controls in field trials and studies; some OEMs have implemented them in commercial products. However, not all OEMs have GFM technology commercially available, and GFM technology is currently most commonly available in BESSs.
- **GFM Resource Capability:** GFM technology does not solve issues associated with fault current levels from IBRs, which are needed for grid protection, as the inverter DC and AC current and voltage limits still dictate their ability to contribute currents and withstand voltages outside nominal ranges.[53] Also, the ability of a GFM IBR to supply significant energy during large disturbance events may be limited by the prime mover and/or by the size of the energy buffer (i.e., dc capacitor). This is inherent in inverter-based technology and not a function of GFM versus GFL controls. Similarly, an IBR's ability to provide FFR or other high-speed energy injection will be dependent on the availability of the power and energy source behind the inverter (e.g., battery, wind speed, solar irradiance). The fault current contribution and protection issue associate with both the GFM and GFL technology needs to be further investigated.
- **GFM as a Solution Option for Low System-Strength Conditions:** GFM controls can operate at very low system-strength levels and do not have the same stability concerns as GFL inverters, so GFM inverter technology is one viable solution among a number of different options to support reliable operation of the BPS at very high IBR penetration levels. Even in cases where synchronous condensers are used to provide fault current, system strength, or system inertia,[54] GFM IBRs may still provide benefits in terms of system stabilization. The following discusses major aspects of GFM inverters operating in low system-strength conditions:
  - In most cases, existing GFL inverters may not need to be modified to GFM; however, existing GFL inverter firmware could be upgraded to support operation in areas with high penetrations of IBRs. It is also possible to supplement GFM IBRs with existing parallel GFL IBRs (e.g., adding new GFM BESS project to existing GFL PV). In some cases, it may be cost effective and beneficial for an existing GFL facility to upgrade to GFM IBRs. It would be beneficial to understand what fraction of the GFL IBR fleet is capable of being updated to GFM controls without a complete repowering of the project. OEMs will need to be heavily involved in this process.
  - TOs, TPs, and PCs should study the reliability of the BPS moving forward under high IBR penetration grid conditions that will require both detailed positive sequences and EMT studies to be conducted to identify situations where existing controls may fail to operate reliably, potentially pointing to the need for GFM controls.

[53] An IBR can be designed to provide higher levels of fault current, but most are not currently designed for it.

[54] Conventional synchronous condensers have relatively small inertia since they do not include a turbine. If synchronous condensers are specifically added for inertia contribution, then a flywheel is most likely needed to increase its overall inertia.

- In areas where conventional GFL controls fail to operate reliably under potential operating conditions, operating limits, such as IBR curtailment, will be established to either limit the instantaneous output of on-line GFL IBRs, or other corrective action plans (e.g., installing synchronous condensers, strengthening the transmission system, retuning GFL controls, or introducing incentives for GFM IBRs) will need to be developed to support increasing levels of IBRs. Societal costs of each solution option should be thoroughly explored to ensure the most cost-effective option to the end-use consumer is selected.
- TOs, TPs, and PCs should clearly identify (where applicable) minimum system strength requirements and provide that information to developers, GOs, GOPs, and OEMs so they understand any requirements regarding low system-strength operations ahead of real-time operation. OEMs may be able to design GFL inverter controls early in the interconnection process to reliably operate under those conditions, or the developer may opt for GFM IBR.
- TOs, TPs, and PCs may also consider other alternative options, such as installing synchronous condensers or strengthening the local transmission, since these solutions provide multiple benefits for grid operations, such as additional reactive power support, short-circuit current contribution for correct protective relay operation, and supporting system strength.

- **Blackstart and Grid Resilience Considerations:** GFM technology provides a significant advantage over conventional GFL technology because GFM inverters can be designed as an initial black-start resource that is not reliant on a strong synchronous grid to reestablish the grid from an outage. Depending on the location of the GFM IBRs in the network, IBRs can serve as a traditional, centralized black start resource or as a distributed black start resource if located at the edge of the grid.[55] Each TOP and RC developing a restoration plan and studying cranking paths should fully understand how any potential GFM IBRs being used in the path would operate. EMT studies are needed to fully understand how the GFM resource will operate under such low system-strength conditions and to validate that the GFM IBR can energize transformers, charge lines, and start motor loads. GFM technology may be able to help shorten outage durations and provide grid resilience; however, energy assurance from variable weather and inverter overcurrent capability will also need to be considered.
- **GFM Limitations:** Although GFM technology shows significant promise in addressing system issues and will play a significant part in future high penetration of IBR scenarios, it is important to recognize that the technology is not without limitations, particularly in the near term while OEMs continue to refine and develop control strategies and hardware configurations. These include the following:
  - The response of the GFM device to system events needs particular considerations on IBR headroom in current, power, and energy. The extent to which these may be limited in a device due to hardware, prime mover, or energy storage constraints may affect the stability and service benefit provided by the device. When a device reaches a physical limit (for example, a current limit during a fault), the GFM controls must accommodate these limits gracefully while continuing to support the network to the greatest possible extent. Failure of the controls to accommodate physical limits in a suitable manner may actually result in degraded system performance. System planners should study the levels of headroom needed for GFM IBRs to provide grid stabilization services and communicate the studied levels to system operators. The desired behavior of GFM controls when approaching physical limits is a topic of research.
  - Use of GFM controls can address instabilities introduced by other IBRs but may also introduce new and unexpected modes of instability into the system. This occurs in the same way that a new synchronous machine may introduce new oscillatory modes into a system or alter existing modes. These will require careful study and potentially new automation strategies or oscillation damping control technology.

[55] https://www.esig.energy/download/session-9-black-start-from-der-vahan-gevorgian/

  - GFM technology is proven to address control stability in areas with low system strength. It does not, however, address long distance high power transfer stability limits based on physical network constraints.
  - As mentioned above, GFM technology is new to the grid, and it should be expected that new issues and limitations will be uncovered as the industry continues to gain experience.

- **Considerations for Utilizing GFM Technology for GOs and GOPs:** TOs, TPs, and PCs will establish performance requirements per the latest effective version of NERC FAC-001, and newly interconnecting resources need to meet those performance requirements. As the grid continues to rapidly evolve, those requirements are also expected to change. As described above, GFM technology introduces flexibility for IBRs to provide grid essential reliability services. Developers and GOs seeking interconnection to low system-strength networks should understand the grid reliability issues associated with operation of GFL technology in those conditions and should explore the use of GFM as one of the viable solution options, working closely with the OEMs and the TP to ensure the GFM is modeled and tuned correctly. System strength will likely continue to decrease over time with the retirement of synchronous generators and increasing levels of GFL IBRs. Therefore, GOs may want to consider moving to GFM technology to enable operation under a wider range of grid conditions and to provide additional grid support capabilities. This is particularly true for BESS and hybrid plant installations.

  GOs should work closely with OEMs regarding coordination of system strength limits established by the TOs, TPs, and PCs. Furthermore, GOs should also work closely with OEMs, any consultants providing modeling support, and the TPs and PCs to ensure EMT models are provided for all applicable GFL and GFM inverter-based resources.

Interconnection Requirements

The following recommendations relate to the establishment of interconnection requirements for GFM technology:

- **Establishing Interconnection Requirements and Conducting Interconnection Studies for GFM Resources:** Each TO, per the latest effective version of NERC FAC-001, is responsible for establishing interconnection requirements for interconnecting new resources to their networks or materially modifying existing resources. TOs are strongly encouraged to fully understand ways GFM technology will operate within their system and should establish clear and consistent requirements for GFM technology to ensure reliable operation of their grid with this new technology. TOs should work closely with their TPs and PCs, per the latest effective version of NERC FAC-002, to ensure adequate models are provided during the interconnection process to reflect the as-built equipment installed in the field. Thorough studies with the sufficiently detailed models should be conducted prior to interconnecting any new resource, and assurance that the GFM controls are appropriately modeled is critical with this new technology. Further, any significant changes in the deployed technology from the models submitted during the interconnection process (GFM controls, settings, topology, ratings, or any other change affecting the electrical behavior of the resources) should initiate a re-study by the TP and PC. The interconnection process should not proceed until those studies have been thoroughly and adequately conducted.
- **Focus on Performance, Not Control Strategy:** GFM control strategies will differ between OEMs. The interconnection requirements should not preclude the use of any one control strategy; rather, the requirements should establish clear performance requirements that the resource must meet and allow any control strategy that can meet or exceed those performance requirements. Interconnection studies will need to be conducted using validated models to represent the full GFM capabilities and characteristics of the resource being supplied.

Modeling and Studies

The following recommendations relate to modeling and studies associated with GFM technology:

- **GFM IBR positive sequence model and transient EMT model:** GFM positive sequence standard library models for grid stability studies are not available to the public at the writing of this document in 2021. OEMs are developing and testing IBR positive sequence models and EMT models with their different GFM IBR controls that contain confidential information and are not open to the public. This will challenge TPs and PCs during their FAC-002 interconnections studies and hinder TP and PC abilities to create interconnection-wide base cases that (in some areas) require the use of standard library models. These issues will need to be addressed to ensure that GFM technology that is already commercially available (and future products) can be effectively studied and integrated into large-scale planning cases.

  While GFL standard library models have the major functions developed, validated, and published in the power system simulation software, it is important for IBR standard library models to include GFM functions as the industry reaches agreement on standardized GFM control types and topologies. Considering the confidential nature of GFM controls and the need for GFM models for planning studies with high penetration of IBRs, it is recommended that the WECC Modeling and Validation Subcommittee or other industry modeling groups start GFM model development with support from OEMs and research organizations in the near future.

- **Study of System Benefits of GFM IBRs:** GFM IBRs will be a critical resource for maintaining stability of the BPS under increasing IBR penetration. These major benefits of the technology can and should be weighed against the incremental costs of leveraging this technology to newly interconnecting resources. It is important to study and coordinate different GFM IBR functions and their specific contributions to overall BPS stability and incorporate those findings into how individual GFM IBR projects are assessed during routine interconnection studies. System-wide reliability studies may also inform the development of both GFM and GFL IBR interconnection requirements.